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Measurement of the effects of the localized field of a magnetic force microscope tip on a 180° domain wall

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Opposite polarity magnetic force microscope (MFM) profiles of domain walls (DWs) in magnetite were measured with a commercial MFM tip magnetized in opposite directions perpendicular to the sample surface. The influence of the tip field on a DW resulted in an overall more attractive interaction. The difference between opposite polarity DW profiles provided a qualitative measurement of the reversible changes in DW structure due to the localized field of the MFM tip. The dependence of the measured alteration on tip-sample separation was fit with a power law at different positions across the DW. The rate of decay of the alteration with tip-sample separation, quantified by the exponent of the power law fit, varied across the DW and was much slower than expected from a simple model. © *1997 American Institute of Physics.* [S0021-8979(97)38708-8]

INTRODUCTION

The field due to a magnetic force microscope[1] (MFM) tip both complicates the use of the MFM as a high resolution probe of micromagnetic structure,[2] and allows localized manipulation of the sample magnetization.[3,4] Although MFM data analysis has often been based on the assumption that no alteration of the sample or tip magnetizations occurred while imaging, numerous investigations of magnetically soft samples have demonstrated the perturbation of the sample micromagnetic structure by the tip field.[5–9] In this work, we studied 180° domain walls (DWs) in magnetite (Fe_3O_4) single crystals.[10,11] The fine micromagnetic structure of these DWs was found to be susceptible to the tip field; however, no translation of the DWs due to the tip field was observed, making these DWs interesting subjects for investigation of the perturbative effects of the tip field during MFM measurements.

In general, the magnetization of a sample will tend to orient along the applied field. This is true whether the field is a macroscopically uniform field such as that from a laboratory electromagnet or a microscopic field such as the stray field from an MFM tip. In the case of the field from an MFM tip, the reconfiguration of the sample spins results in an interaction between the tip and sample which is more attractive (i.e., if the overall interaction is repulsive, it becomes less repulsive and if the overall interaction is attractive, it becomes more attractive). With DW profiles measured with opposite tip magnetizations perpendicular to the surface, the additional attractive MFM signal due to the modification of the DW micromagnetic structure was extracted from the data. This experimental work has been described in detail elsewhere.[12] An explanation was provided for the difference between opposite polarity profiles using a model consisting of a bulk Bloch wall with a surface Néel cap in correspondence with the predictions of micromagnetic simulations. In the present article, we will briefly summarize the earlier work and present further analysis of the dependence of the DW perturbation on tip-sample separation. With accurate knowledge of the spatial dependence of the tip field,[13] these measurements can provide qualitative information about the local susceptibility of the sample to a localized magnetic field.[14]

EXPERIMENT

We investigated bulk Fe_3O_4 single crystal samples of thickness ~1 mm prepared as described previously.[12] The {110} sample surfaces which contain two ⟨111⟩ magnetic easy axes allowed observation of classic domain structures with 180°, 109°, and 71° domain boundaries.[15] MFM images of an area containing all three wall types are shown in Fig. 1. Recent two-dimensional micromagnetic modeling predicted the structure of a 180° DW in Fe_3O_4 (Ref. 16) to rotate from Bloch-like in the sample bulk to Néel-like near the surface.[17] This structure can be represented by a simpler model consisting of a magnetic dipole oriented perpendicular to the surface with the top pole approximately one Bloch wall width beneath the surface (representing the bulk Bloch wall portion) and another dipole in the surface plane perpendicular to the DW length (representing the Néel cap portion).[7]

Images and single line traces or profiles of topography and magnetic force gradient were obtained using a Multimode™ MFM and Nanoscope™ III from Digital Instruments operated in tapping/liftmode™.[18] The magnetic force gradient was measured in liftmode by detecting the phase of the oscillating cantilever.[19] Commercially available, thin film coated, MFM tips were used for this work.[20] Hysteresis loops of the magnetically active volumes of these probes were square with coercivities of approximately 400 Oe.[21] Electron holography has provided quantitative magnetic field profiles in close proximity to MFM tips like those used for this work.[13]

The data shown in this work were measured on the vertical 180° DW in Figs. 1(A) and 1(B). This DW was measured at various heights (''lift heights'') above the topogra-

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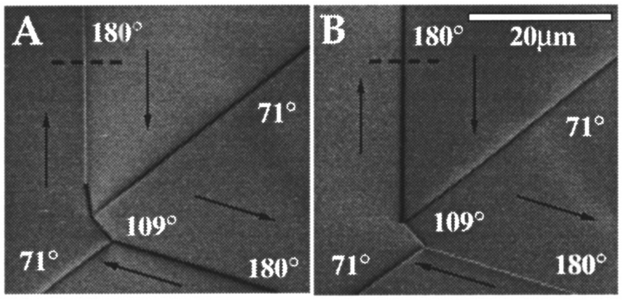

FIG. 1. Two MFM images of the same area of a Fe_3O_4 single crystal containing three types of DWs: 180°, 109°, and 71° as labeled in the images. The MFM tip magnetization perpendicular to the surface for (A) was opposite that for (B). The bold arrows indicate the direction of magnetization in the bulk of each domain. The dashed line across the vertical 180° DW in each image indicates the position where all profiles described later were measured.

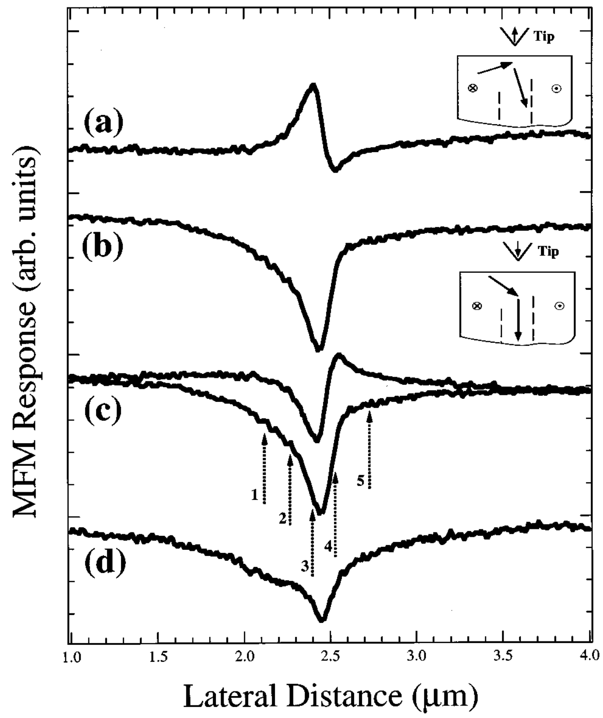

FIG. 2. Two MFM response profiles, (a) and (b), measured above the 180° DW shown in Fig. 1 using the same MFM tip at a lift height of 50 nm. Profile (a) was measured with the MFM tip magnetization antiparallel to the bulk Bloch wall magnetization, i.e., the *repulsive* case. For profile (b) the measurement was *attractive* with the tip magnetization parallel to the bulk Bloch wall. These profiles were obtained by averaging 20 line scans measured successively. Scans made in both directions perpendicular to the wall length were identical. The cartoons inset with profiles (a) and (b) indicate possible alterations of the DW in terms of a simple wall model consisting, in the unperturbed state, of vertical and horizontal dipoles. In (c), profile (a) was inverted and superimposed on profile (b). Profile (d) is the difference profile, [(b)−(-(a))], which shows the additional attractive MFM response due to the effect of the tip field on the DW structure. The numbered arrows indicate the positions along the profile where the difference versus lift height plots in Fig. 3 were taken.

phy profile. Treating the MFM tip as a fixed, point dipole, the magnetic force gradient is a measure of $\partial^2\mathbf{H}_s/\partial z^2$ where $\mathbf{H}_s$ is the sample stray field. The component of the field that is sensed depends on the orientation of the tip moment.[22] The tip was magnetized approximately perpendicular to the sample surface and it was verified that in-plane components of the tip magnetization contributed negligibly to profiles of this DW.[12] Both polarities of profiles, repulsive and attractive (defined according to the sign of the magnetostatic interaction in each case) were measured. For the repulsive profiles, the tip was magnetized antiparallel to the magnetization of the bulk Bloch wall [Fig. 1(A)]. For the attractive profiles, the tip magnetization was reversed [Fig. 1(B)]. Independent of the direction of the tip magnetization, all response profiles across this wall were asymmetric as expected for a combination bulk Bloch wall with a surface Néel cap.[11] However, repeatable differences between repulsive and attractive profiles of the DW were observed, indicating reversible modifications of the DW micromagnetic structure.

RESULTS

A typical pair of repulsive and attractive profiles displaying markedly different asymmetries is shown in Figs. 2(a) and 2(b), respectively. Possible alterations of the DW structure are depicted in the cartoon insets of Fig. 2 for each case in terms of the simple model described earlier. In the repulsive case, the tip field is expected to reduce the vertical DW magnetization relative to the in-plane DW magnetization. In the attractive case, the vertical, symmetric contribution will be enhanced. As can be seen in Fig. 2, the DW profile measurements were consistent with these expectations; the tip field produced a more antisymmetric profile in the repulsive case. In the attractive case, the additional attractive signal due to the tip field resulted in a more symmetric profile. The remaining asymmetry of the attractive profile is consistent with the existence of an intrinsically asymmetric DW structure.

The difference between two opposite polarity profiles is shown in Figs. 2(c) and 2(d). The repulsive profile [Fig. 2(a)] was inverted and superimposed on the attractive profile [Fig. 2(b)] in Fig. 2(c) to highlight the difference.[23] The unperturbed DW profile lies approximately midway between these two profiles. The profile in Fig. 2(d) is the difference between the two profiles in Fig. 2(c), a measure of the combined modifications of the DW from both profile measurements. Again, since the tip field works to align spins parallel to itself and make the magnetostatic interaction more attractive, the modification profile that has been isolated has the correct sign.

With knowledge of the spatial dependence of the tip field, the dependence of the MFM response difference on tip-sample separation can provide information about the local susceptibility of the DW. The MFM response difference, D, versus lift height is plotted in Fig. 3 on a log-log scale for positions along the DW profile indicated in Fig. 2. The lines plotted with the data are the results of fitting each set to a power law, $D = m_0 z^{m_1}$. It can be seen that the slopes of these lines (m_1) vary with position across the DW. The results of power law fitting data from several positions across the DW are summarized in Fig. 4. Away from the DW, m_1 tends toward zero. This is consistent with the fact that there is no difference between MFM signals measured with opposite tip magnetization perpendicular to the plane over a region uni-

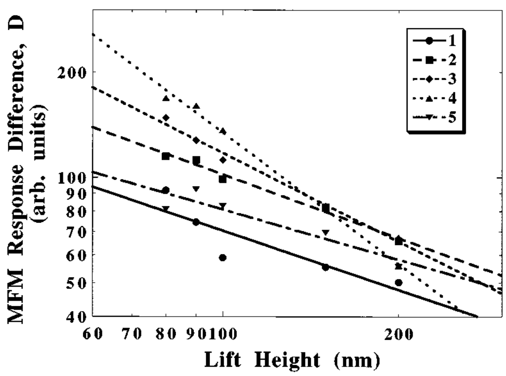

FIG. 3. Log-log plot of MFM response difference vs lift height at various positions across the DW corresponding to the numbered positions in Fig. 2. The lines plotted with the data are the results of fitting each to a power law. The slopes of these lines vary across the DW.

formly magnetized in-plane (when unperturbed). The attractive perturbation signal measured for each tip magnetization results in a null difference at all heights. As the DW is approached, a non-zero response difference becomes measurable and shows an interesting height dependence.

From the work of Streblechenko and co-authors,[13] it is known that the field of our MFM tip, $H_{\rm tip}$, combines dipolar and monopolar contributions, i.e., has terms that decay as z^{-3} and z^{-2}, respectively. If the change in DW magnetization is simply proportional to $H_{\rm tip}$ with a susceptibility, χ_s, the MFM response, $\propto\partial^2\mathbf{H}_{sz}/\partial z^2$, due to $H_{\rm tip}$ decays as z^{-6} (dipolar tip field) and z^{-5} (monopolar tip field) for a DW modeled as a susceptible line of charge with a field that decays as z^{-1}. As seen in Fig. 4, the measured effects of $H_{\rm tip}$ on the DW decay as z^{-p}, where $1.3\geqslant p\geqslant 0.1$. This is much slower than expected from the simple considerations above. Two possible reasons for this discrepancy are: (i) the DW and tip magnetizations are more distributed than the simple models described above and have interactions that decay more slowly than z^{-1}; and (ii) the z dependence of the sample and tip volume have not been considered. Unfortunately, including either of these considerations would require significant computational effort.

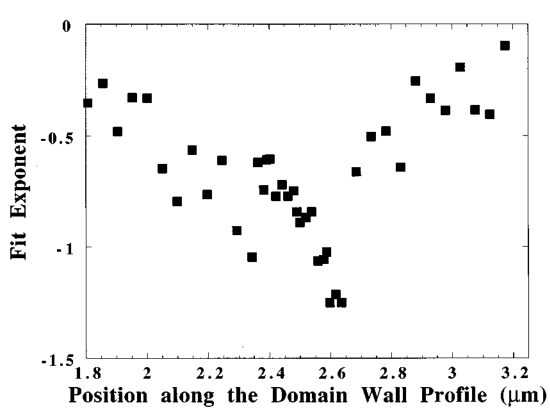

FIG. 4. Results of fitting the MFM response difference to a power law dependence on lift height. Plotted are the exponents (i.e., slopes) obtained for difference vs lift height power law curves at several points across the DW.

In conclusion, we studied the effects of the localized magnetic field of commercial MFM tips on 180° DWs in single crystal Fe_3O_4. Our measurements allowed extraction of changes in MFM DW profiles due to reversible perturbations of the DW micromagnetic structure by the tip field. The dependence of these changes on tip-sample separation was analyzed relative to the previously measured spatial dependence of the tip field. The results of this analysis showed tip–sample interactions that decayed much more slowly than expected from a simple domain wall and tip model. This method, utilizing the field of the MFM tip, allows characterization of the response of micromagnetic structures to a localized applied field.

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[23] Definition of the center of the DW was different for each type of profile measurement; however, care was taken to remain over the same area of the DW for both tip magnetization states using the topography of the area. Furthermore, as profiles were measured repeatedly over the same line, a measure of the lateral drift with time was made and accounted for in aligning the two profiles for calculation of the difference profile.